Determination of Chemical Indicators for the Health and Integrity of Stream Ecosystems in the Bee Creek Watershed

Aaron Waters

Jamie Carpenter

Michael Wasserman

Teresa Bilinski

St. Edward’s University

Wild Basin Creative Research Center

Abstract

Striking a balance between the natural world and cultural development will be at the forefront of any discussion concerning climate change and remediation in the future. Focusing our goals on maintenance of environmental health and integrity is tantamount to global conservation efforts already underway, further emphasizing the need to examine the impacts of all individual actions. The goal of this study was to use an interdisciplinary approach to determine if the recent expansions of suburban development have influenced stream ecosystem health and integrity within the Bee Creek watershed, a 3.3 square mile area surrounding the 3 mile long Bee Creek, a tributary of the Colorado River, and a part of the Edwards Aquifer contributing zone. Our approach employed the measurement of chemical indicators of stream health and integrity, as well as a comparison of our data to historic data from previous studies performed by the City of Austin and the Austin River Watch, in addition to percent land use change since the year 2000, all within the watershed. Using a range of temporally sampled field data, statistical analysis, and geographic information systems for mapping, we identified the suite of parameters that represent the most significant indicators of stream ecosystem health and integrity in the Bee Creek watershed. If a suitable method of measurement is discovered to be an indicator of overall health and integrity, it could be possible to apply it to

many other watersheds as a metric for organizations to use in the development of future environmental policy.

Keywords: watershed, health, integrity, indicators

Introduction

Geological Setting

We focused our study in the Bee Creek watershed, and area located at the southeast portion of the Edwards plateau, immediately adjacent to the Balcones Fault (Smith et al 2013). The Edwards Aquifer covers an area of 4,400 square miles composed mainly of limestone and dolomite. The karst aquifer provides public water supply to more than 1 million people and for agriculture, industry, and military use (USGS 1999). Bee Creek is a 3 mile body running into Lake Austin, with a total area of 3.3 miles (City of Austin 2011). This area is characterized by having an eroded composition of limestone rock (The Nature Conservancy, Edwards Plateau fact sheet) with permeable bedrock which contributes to the recharging of the Edward's Aquifer. The topsoil is classified as Mollisols ultisol (Buol, 2011), which is distinct to semi-arid climates. Much of this land is characterized by steep grades along the creeks of the watershed. The steep grades near the creek can lead to increased runoff from nearby homes, contributing to overall water quality of the watershed. The rock bed is composed of chalk, marl, claystone, but is primarily limestone (Riskind, 2012).

As this site is directly adjacent to the Balcones fault line and rests on porous limestone from the Edwards Aquifer contributing zone (Edwards Aquifer Authority 2013) the water moves from the creek bed to the groundwater, while pressure from the water table pushes to the surface further downstream. This pressure causes approximately 53 million gallons of water to empty into the Colorado River via Austin's Barton Springs Swimming pool every day. The bedrock is composed of limestone which directly contributes to the pH and conductivity. As the Bee Creek watershed is a catchment watershed, much of the water is runoff from precipitation. However, there are nine known springs (City of Austin) within the watershed, the largest of which is Bee Springs, which is now covered due to the construction of the Tom Miller dam. Previous studies indicate that pH can range from 6.75 to 8.75, conductivity has ranged from 600 to over 2500 uS/cm, dissolved oxygen has ranged from 5 to 10 mg/L, ammonia has ranged from 0.01 to 0.25 mg/L, and nitrates have ranged from 0 - 4.5 mg/L (Clamman et. al.). This area is characterized by having an eroded composition of limestone rock with permeable bedrock which contributes to the recharging of the Edward's Aquifer. Parallels will be drawn from an earlier study that found the entire watershed of their tested region comes under the moderate potential recharge zone (Valliammai et al 2013).

Previous Studies

The City of Austin has been collecting data on water quality since 1990 through the volunteer group Water Watchdogs, who transitioned over to full city employee monitoring by 1996. The group created the Environmental Integrity Index (EII) to evaluate water quality. In 2000 the Watershed Protection and Development Review Department implemented quarterly water quality assessment and annual biological and habitat surveys (Clamann, 2013). The WPDRD conducted tests of water sites from 2000-2008, with Bee Creek being considered to be in the Phase 2 category, suburban and developing watersheds, tested in 2001, 2004, and 2007. The next round of tests after site regrouping followed in 2010 and 2012, with Bee Creek in the Phase 2 group again. The city rates the integrity of the creeks that they monitor using an Environmental Integrity Index which measures many of the same parameters as this study, but also includes biological assays including microbial concentrations as well as benthic macroinvertebrate counts. However, their data is limited to only three sites monitored every three years within the watershed. This study will provide a more holistic understanding of water quality, as well as an understanding of the temporal variability in water quality, within the Bee Creek watershed by sampling 7 sites four times each over one month. Our measurements will ensure that the 3 sites historically sampled do not contain data outliers.

Stream Health and Integrity

The quality of stream ecosystem habitat has been defined in several contexts. While the term “stream health” refers to the optimal state of a stream ecosystem influenced by human activities, “stream integrity” refers to sites with little or no influence from human actions (Steedman 1994). A number of studies have applied the “stream health” and “stream integrity” framework to research on the water quality of larger bodies of water that are threatened such as Devils River near Del Rio, Texas (Devils River, 2013), few studies have applied this framework to stream ecosystems (Death et al 2009).

Haskell (1992) argues that a stream is “active and maintains its autonomy over time, and is resilient to stress” while according to Rapport (1989) stream health involves more than “strictly ecological functions” implying that societal demands must also be a consideration has a need in the use of streams. As a cohesive theory, Meyer (1997) postulates that it is necessary to consider both the instrumental and intrinsic values of the stream in order to develop a comprehensive policy concerning the health and integrity of an ecosystem. In addition, according to Meyer (1997) ecologists tend to only consider the intrinsic value of an ecosystem, while the general public, probably think only of what the stream can provide for them, rather than what value the stream has on its own.

To this effect, determining high quality baseline data for the Bee Creek watershed will also play a role in determining what ecosystem services, as defined by the Millennium Ecosystem Assessment, Bee Creek offers the communities that live in and around the watershed. To do this most effectively, we will be studied two sites from the headwaters of the creek located in Wild Basin, as well as five sites positioned downstream at irregular intervals. This sampling method follows the ideas presented by the Rockefeller Foundations' Stroud Water Research Center when, in 1980, the presented the River Continuum Concept. This model states that rivers are a continuum, and their integrity must be considered while observing many characteristics, all of which play a crucial role in determining overall health. Synoptic testing methods will be used to measure the entire stream length over a short time as a means to reduce costs (Lyon et al 2001).

Historic Change, Impermeability, and other Impacts of Urban Surface Runoff in the Bee Creek Watershed

Rapid development in urban and metropolitan areas of watersheds has significantly reduced water quality in the United States in the past 30 years (Coskun et al 2008). Influents of storm water runoff have been linked to decreased bacteriological water quality in urban areas (Ham et al 2009). In the Austin, Texas region there has been a net land use change of 14.76% land use change from permeable limestone to impermeable housing structures over the last 30 years has contributed to an increase in runoff from roads, parking lots, and neighborhoods (City of Austin). As impervious cover increases, so too does runoff, as the water which previously was absorbed by the porous limestone now begins to accumulate in greater volume (Ockerman 1999) into the waterways. This leads to an increased frequency of high intensity flood events within smaller creeks and streams which can contaminate stream ecosystems through the delivery of concentrated levels of pollutants into the watershed (Erickson 2009). Common pollutants introduced by urban and suburban runoff include nutrients from fertilizers, herbicides, chlorine from pool drainage and other harmful chemicals into streams (Hrodey 2009). Much of Bee Creek lies within the Wild Basin Nature preserve, and thus should have a higher water quality index score because the Preserve consists of 227 acres of undeveloped land. Once the creek leaves the Preserve, it enters an area characterized by single family, multifamily and commercial properties before draining into the Lower Colorado River just above the Tom Miller Dam. The current dam has been in existence since 1940, while the previous two in the same location were destroyed by flooding (Tom Miller Dam and Lake Austin, 2014). The rapid development of the City of Austin since then has led to an increase of impervious cover of land and a consequential increase of runoff into the waterways (Yigzaw et al, 2013), which could affect backflow up contributaries such as Bee Creek and influence water quality at the tail end of the stream.

Due to the affluence of the neighborhoods along Bee Creek, many of the homes have swimming pools on their property. While the City of Austin states that private residences may discharge their pool water on the personal property (Clamann 2013), if the residence is located on a hillside, the water will not be absorbed, but rather it will travel down to the creek basin and alter the conductivity of the creek.

Research Objectives and Hypotheses

The Edwards Aquifer feeds water into the streams, rivers, and lakes in much of South-Central Texas (Sutton 2011). Springs and free-flowing wells in the region provide the surface flora and fauna with a source of fresh water (Ross 2011). Increasing urban populations as well as growing agricultural and ranching industries are exerting pressure on the freshwater resources in the region. The rapid urban and suburban development of the Austin area poses serious risk to the quality of stream ecosystems as they travel through areas that are increasingly impacted by human activities (Trowsdale 2007). The quality of surface water runoff is of particularly critical importance for stream health during the periods of drought. As Bee Creek is largely a rainwater catchment, runoff from the homes and businesses within the watershed directly contribute to the chemical composition of the stream.

One of the major threats to the areas freshwater is the resulting contamination of the growing human population. The main objective of this research proposal is to determine what influence urban development has on stream health and integrity by studying historic data from the City of Austin Watershed Protection Department's Bee Creek archive data, and then comparing that data with results from the Wild Basin Wilderness Preserve. Bee Creek passes through preserve land, single-family homes, multi-family homes, and is adjacent to highways and golf courses. In order to provide a sustainable future for water quality in the Austin area, human populations living and working adjacent to stream ecosystems should play an active part in maintaining stream health and integrity. Sharing information about stream health and integrity with the local community is the one effective mechanism for promoting water quality in the region long-term. Our desire is to partner with community leaders and the residents of the Bee Creek watershed so that they may be aware of how their actions influence water quality, and so that these communities can be involved in maintain the overall ecosystem health in the watershed.

To determine our indicators for the Bee Creek ecosystem health, the following hypotheses will be tested:

Primary Hypothesis

Which parameters of water quality directly contribute to overall stream Health and Integrity? Can these be used as determinant variables in the area of the Bee Creek watershed to be used in the future as a measurement of overall health and integrity?

Secondary Hypothesis

Is the Health and Integrity of the creek below Wild Basin compromised due to land use change? Using the parameters from the first hypothesis we measured and compared our findings to historic data from the City of Austin.

From this study, we anticipated that as the land usage has changed from an undeveloped natural environment to a one that supports an increased density of the human element, the health and integrity often suffers as the intrinsic value of this ecosystem is lost to those that only see the area as a utilitarian device to be used as needed. We aimed to determine whether there is a baseline of normalcy that should be maintained, and if those parameters move out of acceptable limits, the cause should be investigated. For example, if conductivity has a spike, what could be the cause? Where would we look to determine the source? This goal of this study was to be able to answer these questions as quickly as possible in the future, thus creating a framework for future watersheds.

Project Significance

The Edwards Aquifer provides the main freshwater resource for Austin and its surrounding areas. Current city population is estimated to be 842,750, and 1,108,403 for Travis County from 2012. The Water Watchdog group began their studies in 1990 with a city population of 465,622 (US Census of Population and Housing). Future estimates put this projected population at 10,984 by 2030, significantly elevated from 2000's level of 2,037 for the watershed (Planning and Development Review Department 2013). The increased demand of water usage and consequential volume of runoff has risen substantially over the past twenty years alone. Human activity in the area, urban, agricultural, and industrial, has put substantial strains on the local ecosystem. This research will provide meaningful data to examine the effect of a growing population on the system and attempt to project the future state of the environment.

Wild Basin was created to protect a patch of urban wilderness in the 1970s and has been a part of the Balcones Canyonland Preserve since 1996. Bee Creek is an ideal location that runs through the protected environment and the encroaching development of homes, major and small roads, and a golf course, all expected to differ with their contributions to runoff.

There are a number of endangered species within the Wilderness Preserve, including the golden-cheeked warblers and the black-capped vireos, both of whom depend upon a clean water source for survival (Barton Creek Habitat Preserve 2009).

Methodology

The seven sample sites were chosen for being locations that contain a constant water supply year round. Sample sites located downstream of Wild basin will be taken at irregular intervals at public spots and by permission from landowners, and the sites within the preserve were granted permission by Travis County (Figure 1).

The first site was the downstream end of the culvert underneath Highway 360, along the southwestern boundary of Wild Basin and marks where the stream first enters the preserve. During the dry months, the water springs up at the culvert, but during winter and periods of precipitation there is water flowing from across the highway. During sample times, small steady amounts of water flowed through the northern culvert, while the southern culvert produced a constant trickling of water adding to the stream. The small eddies outside of the culverts had foamy residue at the surface up to the points where the water mixed, and then the residue continued along the banks.

The second sample site was slightly downstream in Wild Basin at the waterfall, taken at the far end across the pool from the waterfall. The site had tree cover around the sides and reaching over parts of the pool which was relatively calm.

The third sample site was outside of Wild Basin, at the beginning of a residential area. Above the collection site the stream is a wide and deep area with open sky above and moderate tree cover at the edges. The site itself was a private driveway over which the water ran to the downstream side, as well as through 2 culverts beneath the driveway. Water was collected only from the upstream side of the driveway.

The fourth sample site was in an undeveloped site amidst the residential area and had mixed tree cover and open sky. The water levels were low for most of this wide area, and the ground was more porous limestone than previous sites. Further past where the water was collected at this site the water flows underground for a few hundred meters.

The fifth site was at a private residence where the creek runs narrower and around many rocks. The stream runs under open sky largely above the site, and scattered canopy at the site itself.

Site six was beneath the West Lake Drive bridge. The stream here is mostly wide with multiple eddies along the sides and very shallow. The tree cover is mostly open and there are many large rocks throughout this area of the stream.

The seventh sample site was a few hundred meters downstream, to a location at which we believed Bee Creek to meet the backflow from Lake Austin. The water at this location is a deeper pool and appears relatively still and has more pronounced tree cover. Water samples were taken off a small boat dock for canoes and kayaks, and about 50m downstream was a larger private motorboat dock, indicating the amount of water available here that does not exist upstream.

The project monitored and recorded meteorological data from the National Oceanic and Atmospheric Administration, and samples were not taken any sooner than 24 hours from the most recent precipitation event. Samples were collected on site using two portable handheld instruments. Using the Fisher Scientific™ Accumet™ AP85 Portable Waterproof pH/Conductivity Meter (Bier 2009), field measurements of air and water temperatures were taken, while pH, dissolved oxygen, conductivity, and total dissolved solids were measured in the laboratory on campus within 24 hours of collection.

For each parameter we followed procedures from the Accumet AP85 manual (Fisher) in accordance to their methods of calibration to standards. We used the 2.1% temperature coefficient for our analysis of conductivity and total dissolved solids.

Using the Hach DR/890 Field Calorimeter in the laboratory on campus, measurements of the Inorganic Nitrogen, in the form of nitrate concentration, dissolved organic nitrogen in the form of ammonia, total dissolved carbon, and dissolved phosphorous.

Reagents were purchased from Hach to complete field tests. All methods were carried out according to the Hach manual of methods for the DR/890 (DR 800 Series Portable Datalogging Colorimeter Instrument Manual 2009) and Standard Methods for Water and Wastewater (Clesceri 1989).

All sample sites were geographically annotated using a mobile phones and google maps. The data points were recorded and mapped using ESRI's ArcGIS software suite in the GSC84 projection. The ArcGIS model accounted for data from aquifer maps, geologic maps, and simulation models.

Results

This study yielded the following results:

- Air and water temperature are directly correlated
- pH increases along the downstream gradient
- Dissolved Oxygen levels were inconsistent
- Phosphorous levels varied but remained low
- Ammonia levels remained low
- Nitrates decreased along the downstream gradient

- Conductivity/Dissolved Solids decreased along the downstream gradient

Air and water temperatures rose and fell jointly. As a whole, temperatures of both air and water increased from site 1 to site 7, which were collected sequentially. The researchers attributed this increase in temperature to time of day, where collection began in the mornings and ended by early afternoon.

The pH largely increased over the stream from start to finish, but remained within a small range, from 7.68 being the average rating at site 1, 8.02 as the average from site 6, and 7.89 as the average at site 7 where the creek mixes with the backflow from the river.

The levels of dissolved oxygen were inconsistent over the course of the stream. Sites 1, 2, and 3 had on average lower dissolved oxygen levels, while sites 4, 5, and 6 maintained higher levels. Site seven was in flux more than other locations, which the researchers attributed to changes in influx from the river. Sites 1, 2, and 3 were relatively slow flowing, while at sites 4, 5, and 6 the water ran more quickly and had more breakup at the surface from rocks, causing the water to mix with the air more readily.

Phosphorous and ammonia levels were low throughout the stream and remained in a relatively consistent range. This was expected as the study was focused on chemical levels of a stream comprised primarily of groundwater and not including runoff, and low levels of phosphorus and ammonia were anticipated.

Nitrates consistently decreased over stream during each week of the study, as did conductivity and dissolved solids. Nitrate levels started at their highest for the first two sites, dropped at sites 3 and 4 before slightly increasing at 5 and 6, and dropping again at site 7. Conductivity and dissolved solids were reduced sequentially between sites 1 and 7 each week with the exception of site 3 dropping to lower levels than site 6 but higher than site 7.

Discussion

Interpretations within our data set

The original expectation of the researchers was for the baseline water data to have fewer chemical indicators at the head of the stream and through the undeveloped area of Wild Basin, and to contain more contaminants downstream through residential areas. The opposite scenario occurred, where the highest levels of nitrates (Figure 2), conductivity, and dissolved solids initiated at the head of Bee Creek and were reduced over the source of the stream. The expectation is that although no samples were taken within 24 hours of precipitation, there was runoff entering the streambed from across the highway, bringing an influx of contaminants. A large commercial construction site is being developed above the opposite end of the culvert leading into Wild Basin, which the researchers believe may be contributing to the creek.

The results also suggest that nitrates decrease as a function of water temperature, indicating that runoff could be concentrated during warmer months to have a reduced effect (Figure 3).

Analysis with Historic Data

This study compared sites 2, 5, and 7 with the historic data from the City of Austin. COA has taken 20 temporal samples since 2001. Overall the studies were unable to determine significance in data sets. Slight correlations were found between pH and ammonia, dissolved oxygen with ammonia, and nitrates with time. The mean levels for both pH and conductivity increased between the COA testing and this study (Figures 4 and 5).

The historical data was taken at sporadic and irregular intervals, making further correlations inconclusive. More complete data sets would be required to draw more thorough conclusions. The water contributing to the stream from the west side of the highway appears to have affected the levels taken as what was intended to be contributions from groundwater springs. Further testing is recommended during dry seasons to rate the groundwater springs, as well as to gauge creek chemical levels during periods of precipitation to measure runoff being added to the stream at peak flow. Most storm runoff reaches the streams within a day of the precipitation (Booth, 1991) calling for samples to be taken 24 hours after initial rainfall.

Qualitative measurements were given to features such as turbidity, creek flow, and water depth. Future studies would be advised to quantitatively account for each of those factors at each sample location for a more accurate portrayal of the creek.

Broader Impacts

A stream’s structure, design, and function are all subject to land management impact (Einheuser, et al 2013). Understanding the impact that communities have on the water that flows ultimately to the Colorado River is vital to raising awareness of the practices of homeowners everywhere. This is especially relevant to the ubiquitous usage of herbicides and pesticides, the introduction of chlorine from swimming pools into adjacent waterways, and any waste disposal which may drain into an environmentally sensitive area like Bee Creek. The negative impacts of rapid increases in human population on natural resources that are currently occurring in Central Texas is mirrored by global trends. In 1927 human population reached 2 billion, which doubled by 1974, and another 2 billion by 1999 (Cohen). Bee Creek can be used as a microcosm in which to understand how human population growth exerts stress on natural ecosystems.

The West Lake Hills region of Travis County, which houses the Bee Creek Watershed, cites the 2000 population as 3,116 residents, 2010 at 3,520 residents, and projects to have 4,061 by 2020 and 4,561 by 2030 (Texas Water Development Board). The Edwards Aquifer provides water to seven counties in Central Texas, including Austin and San Antonio, the 8th largest city in the United States (The Nature Conservancy, Edwards Plateau fact sheet). Estimates show that while population continues to increase, water resources will decrease by 20 percent across Texas, placing a greater reliance on the quality of water available (Freshwater Conservation 2008). While water runoff is increased by urban development, it has been suggested to be used as recharge water (Diaz-Cruz et al 2008). Further GIS mapping will allow for predicting runoff potential by examining the impervious features. Surface area and materials, as well as proximity to the stream itself, carry different percentages possible for water runoff (Carle, 2005).

Local, state, federal, and international environmental policies are continuing to be put in place, intentionally or reluctantly, and new data from basic stream water quality testing contributes to new protective policy. The significance of the water from the Edwards Aquifer will demonstrate to be high with great local impact. The Clean Water Act mandated state water reports every two years (Niemi et al 2004) to the Environmental Protection Agency for Congress to measure changes and determine modern practices.

The fountain darter is an endangered species found in the area and is highly sensitive to spring flow (Mora et al 2012). The testing done on Bee Creek can better determine the species ability to thrive in the area and establish parameters for better protection of the species.

References

Barton Creek Habitat Preserve: An oasis for endangered species amid Austin suburbs. Austin: The Nature Conservancy, 2009. Print.

Bier, Axel. “Electrochemistry Theory and Practice.” *www.hach.com/smartprobes*. Hach Company, 2010. Web. 19 Nov. 2013.

Bier, Axel W. “pH Measurement in Low-ionic Strength (Pure) Samples.” *www.hach.com/SmartProbes*. 2073 ed. Hach Company, 2009. Web. 19 Nov. 2013.

Booth, Derek B. "Urbanization and the Natural Drainage System - Impacts, Solutions, Prognoses." *The Northwest Environmental Journal* 7.1 (1991): 93-118. Print.

Buol, S. W., Southard, R. J., Graham, R. C., & McDaniel, P. A. (2011). Soil Genesis and Classification. Hoboken : Wiley, 2011.

Carle, Melissa Vernon, Patrick N. Halpen, and Craig A. Stowe. "Patterns Of Watershed Urbanization and Impacts on Water

Quality." *Journal of the American Water Resources Association* June (2005): 693-708. Print.

City of Austin. *Bee Creek Watershed Summary Sheet*. Austin: n.p., 2011. Print.

Clamann, Andrew, Aaron Richter, and Emily Yeoman. *Environmental Integrity Index Phase I & II (2011-2012) Watershed Summary Report*. Austin: City of Austin Watershed Protection, 2013. Print.

Clesceri, Lenore S., Arnold E. Greenberg, and R. Rhodes Trussell, eds. *Standard Methods for the Examination of Water and Wastewater*. 17th ed. 1989. Print.

Cohen, J. E. (2003). Human Population: The Next Half Century. Science, 302(5648), 1172-1175.

Colorado River Watch Network Water Quality Monitoring Manual. Rept. no. 9th Edition. Austin: Lower Colorado River Authority, 2012. Print.

Coskun, H. Gonca, et al. “Determination of Environmental Quality of a Drinking Water Reservoir by Remote Sensing, GIS and Regression Analysis.” *Water, Air & Soil Pollution* 194.1-4 (2008): 275-85. Print.

Damo, Robert, and Pirro Icka. “Evaluation of Water Quality Index for Drinking Water.” *Pol. J. Environ. Stud.* 22.4 (2013): 1045-51.

Print.

Daniel, Edsel B., et al. “Watershed Modeling Using GIS Technology: A Critical Review.” *Journal of Spatial Hydrology* 10.2 (2010): n. pag. Print.

Death, Russell G., Zoe S. Dewson, and Alexander B.W. James. “Is structure or function a better measure of the effects of water abstraction on ecosystem integrity?” *Freshwater Biology* 54.10 (2009): 2037-50. Print.

"Devils River." The Nature Conservancy. The Nature Conservancy, n.d. Web. 5 Dec. 2013. http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/texas/placesweprotect/devils-river-fact-sheet-1008-lowres-1.pdf>.

Diaz-Cruz, M. Silva, and Damia Barcelo. “Trace organic chemicals contamination in ground water.” *Chemosphere* 72.3 (2008): 333-42. Print.

“DR/820, DR/850, DR/890.” *DR 800 Series Portable Datalogging Colorimeter Instrument Manual*. Loveland: Hach Company, 2009. 1-8. Print.

"Edwards Aquifer Region." Map. Edwards Aquifer Authority. Edwards Aquifer Authority, n.d. Web. 4 Dec. 2013. <http://www.edwardsaquifer.org>.

The Edwards Plateau Ecoregion: Extraordinary diversity of life amid hills and canyons in Central Texas. San Antonio: The Nature Conservancy, 2008. Print.

Einheuser, Matthew, et al. “Linking Biological Integrity and Watershed Models to Assess the Impacts of Historical Land Use and Climate Changes on Stream Health.” *Environmental Management* 51.6 (2013): 1147-63. Print.

Erickson, Timothy O., and Heinz G. Stefan. *Groundwater Recharge in a Coldwater Stream Watershed during Urbanization*. Rept. no. 524. Minneapolis: University of Minnesota, 2009. Print.

Freshwater Conservation: Protecting our most important natural resource. San Antonio: The Nature Conservancy, 2008. Print.

Fryar, Alan E., et al. “Nitrate reduction during ground-water recharge, Southern High Plains, Texas.” *Journal of Contaminant Hydrology* 40.4 (2000): 335-63. Print.

Geographic Information Systems. “Development Web Map.” Map. *AustinTexas*. City of Austin, n.d. Web. 21 Nov. 2013. <http://www.austintexas.gov/GIS/developmentwebmap/Viewer.aspx>. selected ‘creeks by type’ and ‘watershed features’ on map

Ham, Young-Sik, Hiromi Kobori, and Masahisa Takasago. “Effects of combined sewer overflow and stormwater on indicator bacteria concentrations in the Tama River due to the high population density of Tokyo Metropolitan area." *Environmental Monitoring & Assessment* 152.1-4 (2009): 459-68. Print.

Haskell, B. D., B. G. Norton, and R. Costanza. "What is ecosystem health and why should we worry about it?" *Ecosystem Health*. Ed. R. Costanza, B. G. Norton, and B. D. Haskell. Washington, D.C.: Island Press, 1992. 3-22. Print. HASKELL, B. D., B. G. NORTON, AND R. COSTANZA. 1992.

Hrodey, Peter J., et al. "Land-use Impacts on Watershed Health and Integrity in Indiana Warmwater Streams." *American Midland Naturalist* 161.1 (2009): 76-95. Print.

Lyon, Steve W., Hendrik Braun, and Johan Temnerud. "Accounting for instream lakes when interpolating stream water chemistry observations." *Journal of Spatial Hydrology* 11.2 (2011): n. pag. Print.

Meyer, Judy L. "Stream Health: Incorporating the Human Dimension to Advance Stream Ecology." *Journal of the North American Benthological Society* 16.2 (1997): 439-47. Print.

Mora, Miguel A., et al. "Simulated effects of reduced spring flow from the Edwards Aquifer on population size of the fountain darter (Etheostoma fonticola)." *Elsevier* (2012): 235-43. Print.

Natural Subregions of Texas. Map. Texas Parks and Wildlife Department, 2011. Print.

Niemi, Gerald J., and Michael E. McDonald. “Application of Ecological Indicators.” *Annual Review of Ecology, Evolution, and Systematics* 35 (2004): 89-111. Print.

Operating Instructions. accumet AP85 Portable Waterproof pH/Conductivity Meter. N.p.: Fisher Scientific, n.d. Print.

“Planning and Development Review Department: Demographics.” *AustinTexas*. City of Austin, Apr. 2013. Web. 21 Nov. 2013. <http://austintexas.gov/demographics>.

Rapport, D. J. “What constitutes ecosystem health?” *Perspectives in Biology and Medicine* 33 (1989): 120-32. Print.

Riskind, David H., and David D. Diamond. *The Balcones Escarpment: Plant Communities of the Edwards Plateau of Texas: an Overview Emphasizing the Balcones Escarpement Zone Between San Antonio and Austin with Special Attention to Landscape Contrasts and Natural Diversity*. Austin: Geological Society of Ameria, 2012. Print.

Ross, Lauren. *Land-Applied Wastewater Effluent Impacts on the Edwards Aquifer*. N.p.: Glenrose Engineering, Inc., 2011. Print.

Smith, Brian, and Brian Hunt. “Enhanced recharge to the Barton Springs segment of the Edwards Aquifer, Central Texas.”

Carbonates & Evaporites 28.1/2 (2013): 67-73. Print.

Steedman, Robert J. "Ecosystem Health as a Management Goal." *Journal of North American Benthological Society* 13.4 (1994): 605-10. Print.

Sutton, Leslie Jo. *The Recharge and Discharge of the Edwards Aquifer Located in South-Central Texas*. Austin: n.p., 2011. Print.

"Tom Miller Dam and Lake Austin." *Lower Colorado River Authority*. Austin: n.p., 2014. *Tom Miller Dam and Lake Austin*. Web. 3 May 2014. http://www.lcra.org/water/dams-and-lakes/pages/miller-dam.aspx

Trowsdale, S. A., and D. N. Lerner. "A modelling approach to determine the origin of urban ground water." *Journal of Contaminant Hydrology* 91.1-2 (2007): 171-83. Print.

United States. Environmental Protection Agency. *Methods for the Determination of Total Organic Carbon (TOC) In Soils and Sediments*. Rept. NCEA-C-1282. Print.

US Census of Population and Housing. *1990 Census: Population of Texas Cities*. Print.

U.S. Department of the Interior. U.S. Geological Survey. *Stormwater Runoff for Selected Watersheds in the Edwards Aquifer Recharge*

Zone, Bexas County, Texas, 1996-98. By D.J. Ockerman, B.L. Petri, and R.N. Slattery. San Antonio: U.S. Geological Survey, 1999. Print.

Valliammai, A., et al. “Identification of potential recharge zone of the selected watershed using Remote Sensing and GIS.” *International Journal of Scientific & Engineering Research* 4.8 (2013): n. pag. Print.

West Lake Hills Wastewater Collection System Map. Map. Austin: K Friese and Associates, Inc., 2013. West Lake Hills. Print.

Yigzaw, Wondmagegn, Faisal Hossain, and Alfred Kalyanapu. "Comparison of PMP-Driven Probable Maximum Floods with Flood Magnitudes due to Increasingly Urbanized Catchment: The Case of American River Watershed." *Earth Interactions* 17.8 (2013): 1-15. Print.

Figures and Tables

Figure 1

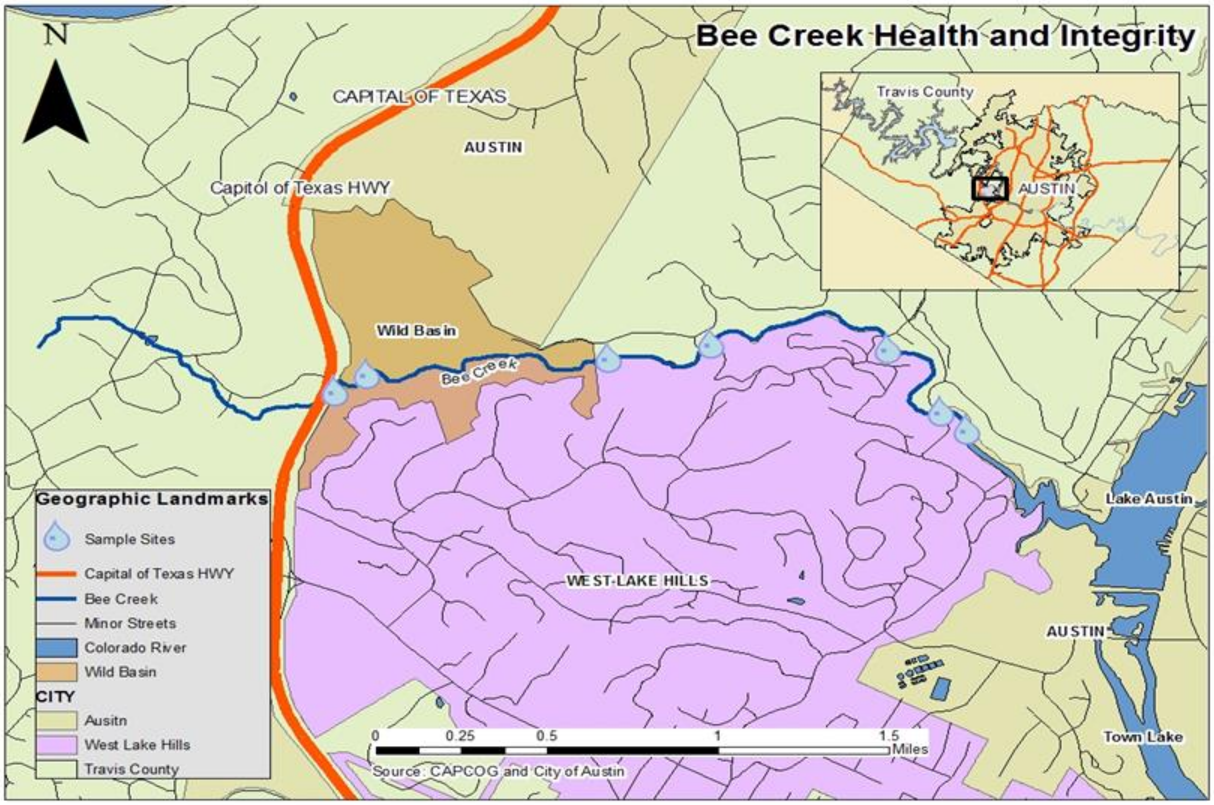


Figure 2

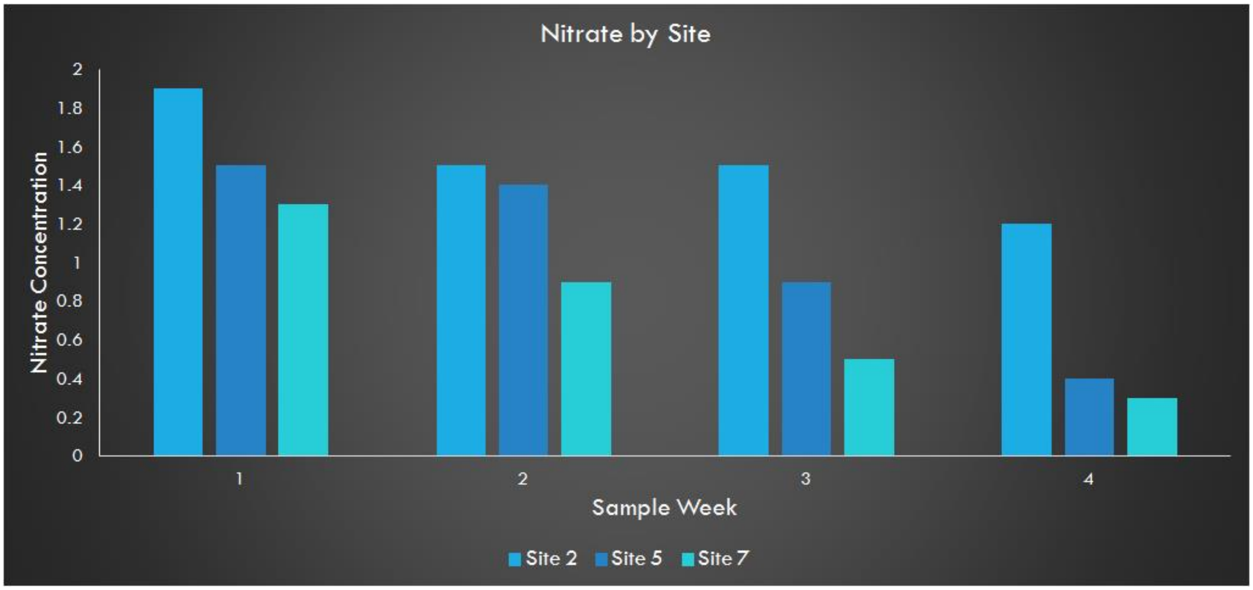


Figure 3

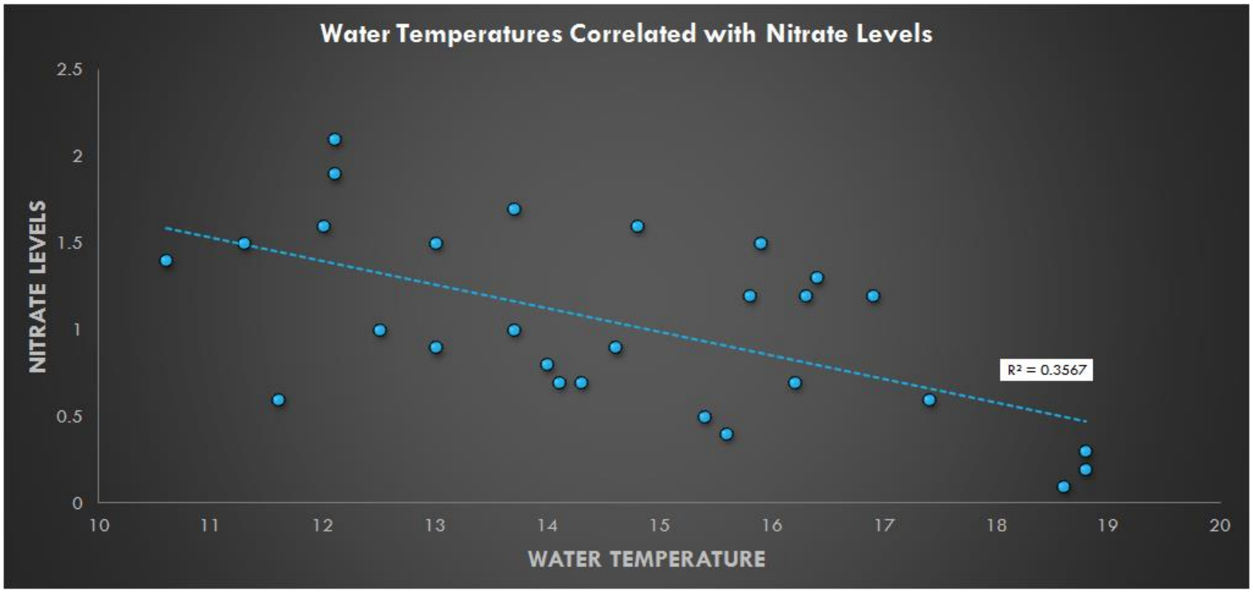


Figure 4

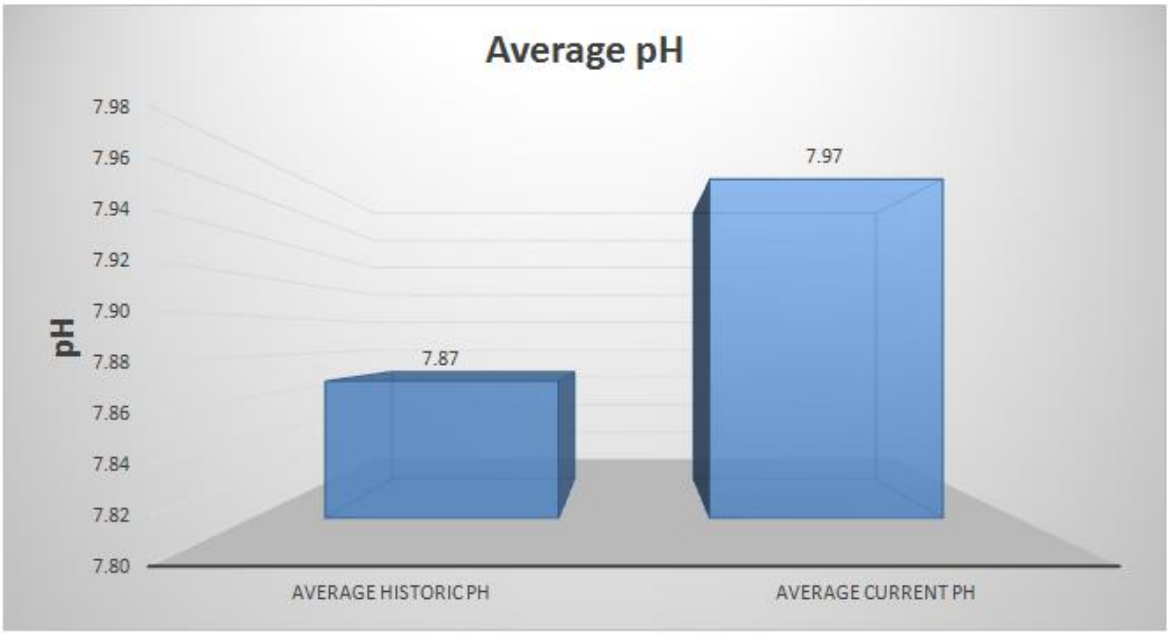
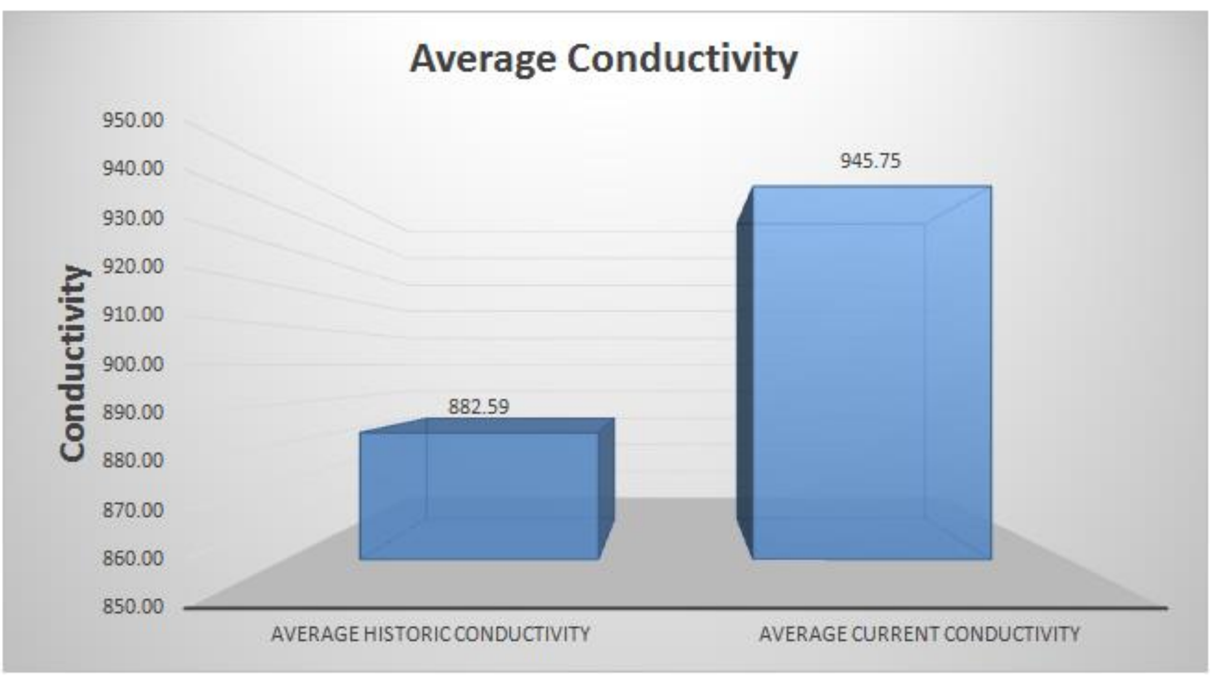


Figure 5



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Wild Basin Creative Research Center

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